METHOD OF STUDYING THE REACTIONS OF A HUMAN OPERATOR CONSIDERED AS AN OSCILLATORY SYSTEM TO HARMONIC AND RANDOM VIBRATIONAL ACTION

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ABSTRACT. Results of an experimental
study of the dynamic responses and functional
state of a human operator subjected to harmonic
and random vibrational excitation. A number
of problems involved in obtaining objective
estimates of the effect of vibrations of various
types and spectral compositions on human
operators are considered. Some possible ways
of constructing human-operator models which
are essentially nonlinear oscillatory systems
of complex dynamical structure are indicated,
and methods of investigating these models are
suggested.

INTRODUCTION

In recent years, due to the development of various new   /695*
branches of technology and the creation of new modern machines,
automatic lines, devices, and flight vehicles controlled by a
human operator a number of new problems arose in which it was
necessary to estimate the working ability of a human operator
under various conditions and to analyze the physiological conse-
quences of the action of various physical factors on the human
operator, as a result of his interaction with a machine.

In the USSR particular attention is given to the study of
physiological changes in the organism of a human operator, arising

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*Numbers in the margin indicate pagination in the foreign text.

1

under the influence of various physical factors during industrial activity. The fundamental objective of that study is to design machines that will be safe for the health of human beings [1-13].

In England, France, and particularly in the United States, extensive scientific studies are conducted aimed at a comprehensive appraisal of the behavior of a human being operating a machine so that efficient machine designs can be developed [14-16].

Among those questions, the problem of the effect of machine vibrations and the noise generated by them on the human operator's organism is at the present time one of the most urgent problems. The problem of the effect of vibrations on the human operator, in spite of its urgency, has not thus far been sufficiently studied. For this reason, the present paper poses a number of new problems related to the objective estimate of the effect of vibrations of various forms and spectral composition on human beings.

Formulation of the Problem

The human body in our case is regarded as a mechanical system consisting of concentrated masses, springs, and dampers. That system is subject to the action of vibrations mediated either through the hand of a standing human operator or through the chair /696 in which he sits. The output signal is in the form of the vibrational acceleration of the human operator's head, since it is the vibrations of the head that affect substantially the performance of the operator's chief functions. Starting with the experimental recording of the input and output signals, we must determine the frequency response of the human body and find the parameters of the concentrated mechanical elements that constitute the mechanical model of a human body.

In this article, the objective of creating a dynamic model of a human being subject to vibrational action was pursued by making measurements for various postures and muscle tensions.

When studying the "pelvis-head" system, the characteristics were determined for three different human postures: without muscular tension, the man is grouped together, the spinal column is straight, hands are raised upward, muscles are slightly flexed. For the "hand-head" system, the tension in the muscles of the hand was varied.

A short description of the method used to solve the problem is now given.

The basic principles of correlation methods were used to determine the dynamic characteristics.

The relation between the input signal x(t) and the output signal y(t) for a linear stationary system can be written as

$$y(t) = \int_0^\infty g(\tau) x(t-\tau) d\tau,$$ (1)

where g(t) is an impulse transfer function of the system.

Multiplying Equation (1) by x(t-α) and taking its time average, we obtain

$$K_{xy}(\alpha) = \int_0^\infty g(\tau) K_{xx}(\alpha-\tau) d\tau,$$ (2)

where $K_{xy}(t)$ is the correlation function of the signals.

$K_{xx}(t)$ is the autocorrelation function for the input signal.

Applying the Fourier transform to Equation (2), we obtain

$$H_{xy}'(j\omega) = W(j\omega)H_{xx}(j\omega),$$

<div align="right">(3)</div>

where $H_{xy}(j\omega)$ is the mutual spectral density of the signals $x(t)$ and $y(t)$, $H_{xx}(j\omega)$ is the spectral density of the signal $x(t)$, $W(j\omega)$ is the transfer function for the system.

In order to estimate the mean square level of vibrations for the human operator's head for any real disturbance whose spectral characteristics are known, it is sufficient to determine the modulus of the transfer function of the system. The mean square reaction of the system to wide-band vibrations is calculated as follows

$$\sigma = \sqrt{\int_{f_1}^{f_2} T^2(f)S(f)\,df},$$

<div align="right">(4)   /698</div>

where $T(f)$ is the modulus of the transfer function of the system, $S(t)$ is the spectral density of the perturbing vibration. In case the system is not linear, we can use the method of statistical linearization when the dynamics of the system for small perturbations can approximately be described linearly. For a stable stationary system, this is equivalent to the minimization of the mean square error

$$\varepsilon = M\left[y(t) - \int_0^\infty x(t-\tau)g(\tau)\,d\tau\right]^2.$$

<div align="right">(5)</div>

Now let us increment the impulse transfer function $g(\tau)$ by /699
$\Delta g(\tau)$, and determine the increment in the error from

$$\varepsilon + \Delta\varepsilon = M\left\{y(t) - \int_0^\infty x(t-\tau)[g(\tau) + \Delta g(\tau)]\,d\tau\right\}^2$$

<div align="right">(6)</div>

Then it is easy to see that min ε will hold when Condition 1 is satisfied. One can also use the method of a generalized model

of a nonlinear system. We know that a nonlinear system can be described by means of the functional Volterra series whose terms are in the form of convolution integrals

$$y(t)=\int_{-\infty}^{t} x(\tau_1) h_1(t-\tau_1)d\tau_1 + \int_{-\infty}^{t}\int_{-\infty}^{t} x(\tau_1) x(\tau_2) h_2(t-\tau_1, t-\tau_2)d\tau_1 d\tau_2 + \cdots \qquad (7)$$

or in the final form for a stable system

$$y(t)=\sum_i a_i x(t-\tau_i) + \sum_i \sum_j a_{ij} x(t-\tau_i) x(t-\tau_j) + \cdots$$
$$+ \sum_i \sum_j \cdots \sum_k a_{ij\ldots k} \prod_i^k x(t-\tau_k). \qquad (8)$$

Minimizing the error for fixed values of the coefficient $a_{ij\ldots k}$, we obtain

$$\varepsilon_i = \frac{1}{2}\frac{\partial \sigma^2}{\partial a_i^2} = \sigma \cdot \hat{x}_i$$
$$\varepsilon_{ij} = \frac{1}{2}\frac{\partial \sigma^2}{\partial a_{ij}} = \sigma \cdot \hat{x}_i \hat{x}_j$$
$$\cdots \cdots \cdots \cdots$$
$$\varepsilon_{ij\ldots k} = \frac{1}{2}\frac{\partial \sigma^2}{\partial a_{ij\ldots k}} = \sigma \cdot \hat{x}_i \hat{x}_j \ldots \hat{x}_k , \qquad (9)$$

where $x_i = x(t-\tau_i)$, $x_{ij} = x(t-\tau_i)x(t-\tau_j)$, etc.
This gives a vector equation

$$\theta = M\Gamma - \Xi . \qquad (10)$$

This equation can be solved either analytically or on a model by means of a direct selection of the kernels $a_{ij\ldots k}$ that determine the nonlinear system. The matrix Ξ is completely determined by the character of the input signal x(t).

The experiment designed to investigate the reactions of the dynamic "pelvis-head" system to random perturbing actions in the frequency range from 3 to 250 Hz was conducted using a special experimental setup which included a vibro-stand, random noise

generator, and amplifier. We measured the vibrational accelera-
tion on a platform with a man sitting on it and the vibrations
of the subject's head. Piezoelectric sensors were used to moni-
tor the accelerations. A special helmet was used to attach the
sensors to the head. In the course of the investigations, it
was established that the dynamic characteristics strongly depend
on the posture and degree of muscular tension.

The recordings of the input and output signals were quan-
tized in time. The magnitude of the quantization step was
selected using the Nyquist method for f_b = 250 Hz. The recording
continued for 2.5 seconds with f_N = 3 Hz being the lowest
frequency of the process. The basic statistical characteristics
of the distributions and their moments, correlation functions,
and spectral densities were found on the BESM computer. In this
case, the process under investigation was pre-centered. The
experimental distributions thus found of the instantaneous values
of signals had a shape close to normal. The calculated moments
of asymmetry and excess are small, which confirms the hypothesis
that the experimental distributions are normal. Since the
experimental distributions at the input to and output from the
system are constant, then for the time interval in question the
system may be considered stationary and linear.

An analysis of the correlation functions shows that both
the input and output processes have a periodic structure. It
was also established that the output signal for a given recording
interval is stationary and ergodic. The analytic expression for
the correlation functions of the system's output was assumed to
have the form

$$k = \sum a_g e^{-\alpha_g \tau} \cos \omega_g \tau,$$

where a_q is a weighting coefficient of the qth harmonic. Using a direct cosine Fourier inverter on the experimental correlation functions, we determined the normalized functions of the spectral input and output densities for all postures investigated.

A comparison of the spectral input and output densities shows that the human body may be considered as a narrow-band filter. Knowing the analytic expression for the correlation function, one can also easily find the expression for the functions of spectral densities. The parameters α_q and ω_q were found from the experimental functions of spectral densities: ω_q is the frequency of the qth maximum in rad/sec, α_q is the half-width of the qth maximum in Hz at the 0.5 $S(\omega)$. Using the experimental spectral densities, we found the amplitude-frequency characteristics of the "pelvis-head" system for each of the postures investigated (Figures 1, 2, 3). The frequency responses thus found permit us to determine the resonant frequencies and to construct a structural model of the system. As indicated above, the resonant frequencies depend greatly on the posture. For posture I, these frequencies are 4, 12, 36 Hz. When the posture is changed, one observes a frequency shift. Thus, for the postures P and Sh these frequencies were a - 32, ..., and 20, 25, 45 Hz, respectively. The smallest width of the passband corresponds to the posture P whose frequency characteristic is narrow-band with a sharply defined maximum at the frequency of 8 Hz. In this case, the system may be replaced with a single mass model. For the postures Sh and 1, the system may be replaced with 3- and 5-mass models, respectively. One should note the fact that the elastic and damping properties of the system which determine the oscillations of the human head greatly depend on the position of the spinal column in space.
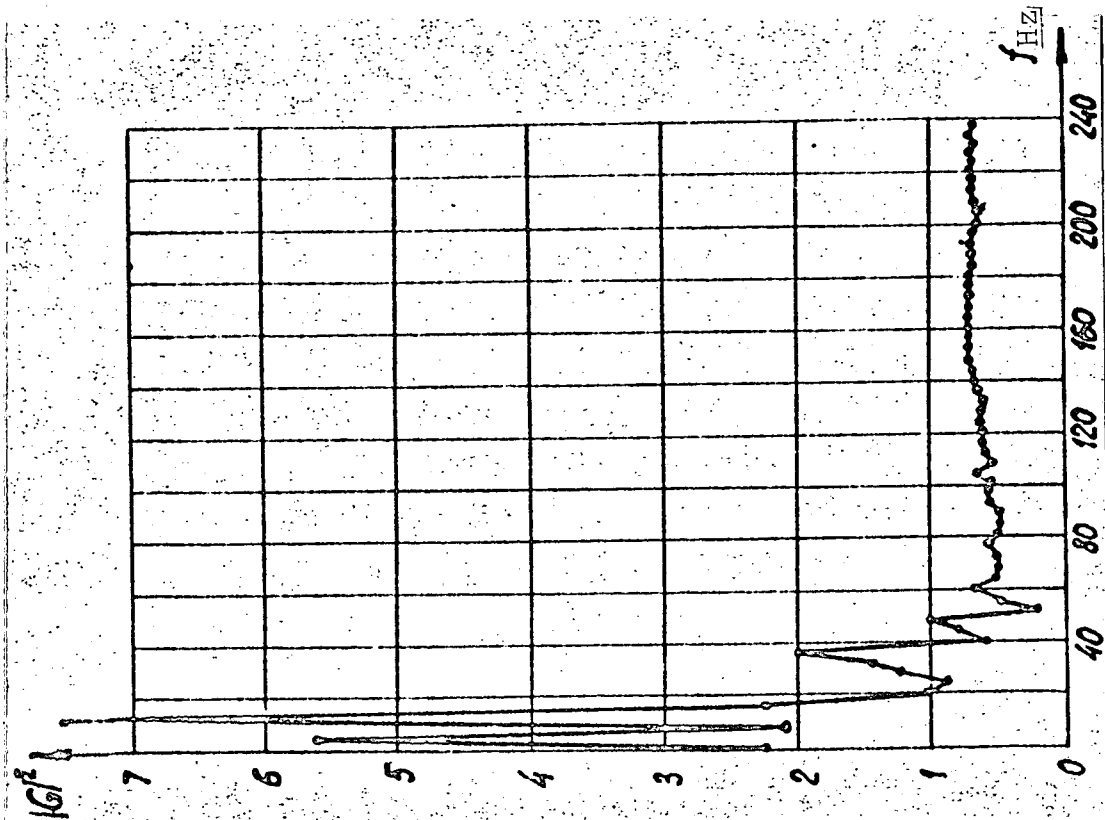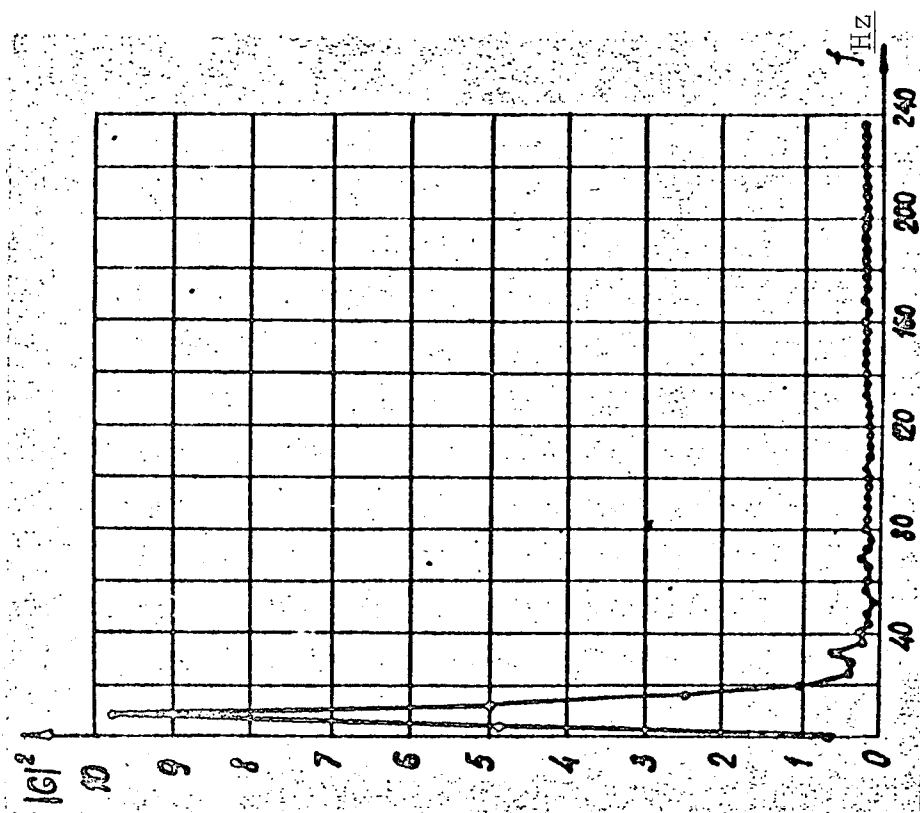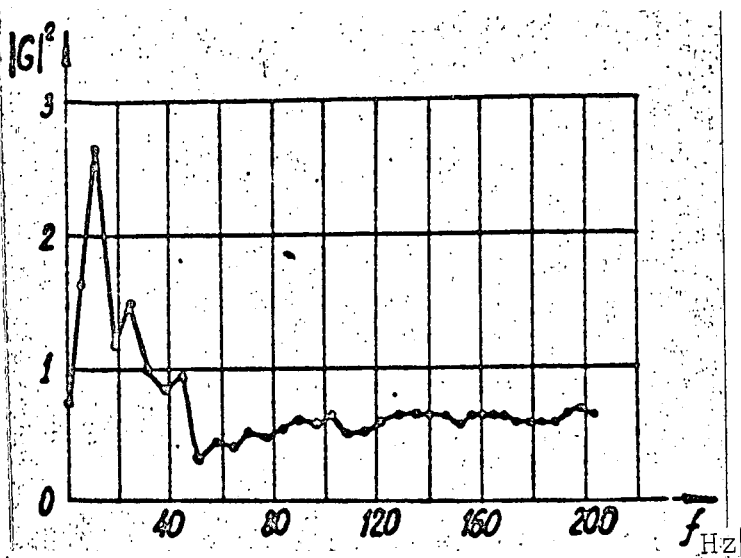
Figure 2

Figure 1

8

Figure 3.

The experimental frequency responses thus obtained enable us to predict the oscillations of the human head for any given external disturbances. As an example, the paper includes an estimate of the expected vibrational accelerations of a cosmonaut's head during the firing of a rocket's third stage for the posture Sh. The spectral densities of a satellite's vibrations were taken from the published papers [17].

The mean square accelerations obtained were 2.18 q, which is approximately ten times higher than the accelerations experienced by a passenger in a soft railroad car. Introducing an acceleration minimum criterion or any time-dependent criterion, it is not hard to estimate the physiological effect of vibrations. In this case, one can solve the problem of optimum vibrational protection of a human being by determining the necessary posture /702 and a given duration of the process or, if this is impossible, by changing the parameters of the external influence.

In conclusion, the author wishes to take advantage of this opportunity and express his gratitude to B. A. Potemkin and B. N. Kashkov for their participation in the experiments and the analysis of the data obtained.

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12